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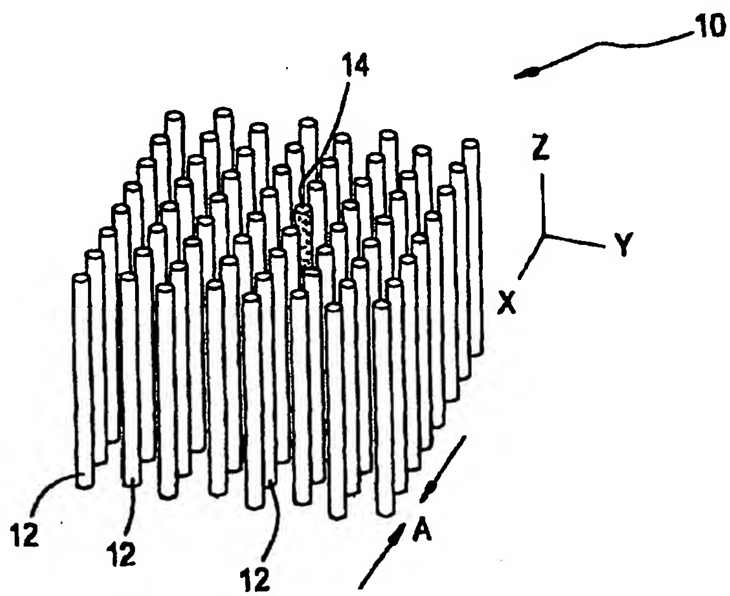


(57) Abstract: A fiber optic waveguide is disclosed. The fiber optic waveguide includes a core region, and a cladding region surrounding the core region. The cladding region includes an inner cladding region and an outer cladding region. The inner cladding region has a lattice of large diameter columns. The lattice of large diameter columns have a diameter (d) to pitch (Λ) ratio defined by the relationship d/Λ greater than or equal to 0.3.

WO 01/37008 A2

PHOTONIC CRYSTAL FIBERS WITH HIGH RESISTANCE TO BEND LOSS

Background of the Invention

1. Field of the Invention

The present invention relates generally to a photonic crystal optical waveguide structure for an optical communication system. More particularly, the present invention is directed to a photonic crystal fiber structure which is highly resistant to bend loss.

2. Technical Background

The investigation of properties of specific optical fiber designs has continued to keep pace with an ever increasing demand for high capacity, long haul waveguide fiber. Data transmission rates in the terrabit range are being studied and communication systems having regenerator spacings greater than 100 km are under consideration. The requirement in the telecommunication industry for greater information capacity over long distances, without regenerators, has led to a reevaluation of single mode fiber index design.

Optical waveguide fibers can be generally classified into single-mode fiber and multimode fiber. Both types of optical fiber rely on total internal reflection (TIR) for guiding the photons along the fiber core. Typically, the core diameter of single-mode fiber is relatively small, thus allowing only a single mode of light wavelengths to propagate along the waveguide. Single-mode fiber can generally provide higher bandwidth because the light pulses can be spaced closer together, and are less affected by dispersion along the fiber. Additionally, the rate of power attenuation for the propagating light is lower in a single-mode fiber. Optical fibers which maintain their single mode characteristics for all wavelengths are defined as endlessly single mode fibers.

Optical fibers having a larger core diameter are generally classified as multimode

fibers, and allow multiple modes of light wavelengths to propagate along the waveguide. The multiple modes travel at different velocities. This difference in group velocities of the modes results in different travel times, causing a broadening of the light pulses propagating along the waveguide. This effect is referred to as modal dispersion, and limits the speed at which the pulses can be transmitted; in turn limiting the bandwidth of multimode fiber. Graded-index multimode fiber (as opposed to step-index multimode fiber) has been developed to limit the effects of modal dispersion. However, current multimode and graded-index multimode fiber designs still do not have the bandwidth capabilities of single-mode fiber.

Photonic crystals are another means by which photons (light modes) can be guided through an optical waveguide structure. Rather than guiding photons using TIR, photonic crystals rely on Bragg scattering for guiding the light. The characteristic defining a photonic crystal structure is the periodicity of dielectric material along one or more axes. Thus, photonic crystals can be one-dimensional, two-dimensional and three-dimensional. These crystals are designed to have photonic band gaps which prevent light from propagating in certain directions within the crystal structure. Generally, photonic crystals are formed from a periodic lattice of dielectric material. When the dielectric constants of the materials forming the lattice are different, and the material absorbs minimal light, the effects of scattering and Bragg diffraction at the lattice interfaces allow the photons to be guided along or through the photonic crystal structure.

An exemplary photonic crystal 10 which is periodic in two directions and homogeneous in a third is shown in Figure 1. More specifically, photonic crystal 10 comprises a triangular lattice of dielectric columns 12, extending in the Z-axis direction, which are periodic in the X-axis and Y-axis directions (measured center to center). The photonic crystal 10 is assumed to be homogeneous in the Z-axis direction. As a result of this structure, photonic band gaps may be created in the plane of periodicity (X and Y planes).

It is also known that a defect can be introduced into the crystalline structure for altering the planar propagation characteristics and localizing the light modes. For example, photonic crystal 10 includes a central column 14 (shown as a solid black column) comprising a dielectric material that is different from the other periodic columns 12. Additionally, the size and shape of central column 14 can be modified for perturbing the

single lattice site.

The characteristics of the crystalline structure produce a photonic band gap (PBG). The defect in the crystalline structure allows a path for light to travel through the crystal. In effect the central column 14 creates a central cavity which is surrounded by reflecting walls. Light propagating through the central column 14 (along the Z-axis direction) becomes trapped within the resulting photonic band gap and cannot escape into the surrounding periodic columns 12. Thus it has been demonstrated that light, whether a pulse or continuous light, can also be guided through this type of photonic band gap crystal. These same structures can be used as effective index structures where the defect acts as a high index core region for guiding light by total internal reflection.

An optical waveguide fiber having a photonic crystal cladding region known within the prior art is shown in Figure 2. The photonic crystal fiber (PCF) 16 includes a porous clad layer 18, containing an array of air voids 20 that serve to change the effective refractive index of the clad layer 18. This in turn serves to change the properties of the fiber 16 such as the mode field diameter or total dispersion. The air voids 20 defining the clad layer 18 create a periodic matrix around the central fiber core 22, usually formed from solid silica. The distribution of light power across the waveguide (mode power distribution) effectively determines the properties of the optical waveguide. Changing the effective index of the clad layer 18 changes the mode power distribution and thus the properties of the PCF optical waveguide 16.

As shown, the air voids 20 are spaced from each other by a constant pitch. Additionally, each air void 20 has a relatively small diameter with respect to the pitch. Generally, in previous designs this relationship can be represented by $d/\Lambda < 0.3$ where d is the diameter of the air void or column, and Λ (lambda) is the center-to-center spacing or pitch of the air voids or columns. As a result, PCF 16 is highly susceptible to bend losses when a length of the optical fiber forms a radius because of the smaller diameter air voids. For the PCF 16 shown in Figure 2, the pitch (Λ) of air voids 20 is about $\Lambda = 4.4$ microns and $d/\Lambda = 0.25$. One skilled in the art will appreciate that d/Λ must satisfy the condition $d/\Lambda < 1.0$ when the columns 20 are air voids, otherwise the structure will collapse because the diameter (d) of the air voids 20 will equal or exceed the pitch (Λ), and the structure will collapse. Figure 3 is a graph showing the bend loss characteristics of

PCF 16 shown in Figure 2. As will be appreciated, one problem observed with PCF 16 is the high bend loss characteristic for all radii tested. Figure 3 shows the attenuation characteristics associated with PCF 16, which is a single mode optical fiber. As will also be appreciated, Figure 3 shows the presence of both long and short wavelength bend edges.

An advantage realized through PCF structures is that the large contrast between core and clad effective index afforded by these structures can be used to provide large effective area, thereby mitigating non-linear effects on transmitted signal integrity. In view of the advantages associated with photonic crystal fiber structures, it is desirable to provide an optical waveguide PCF which reduces problems associated with "bend loss" over sections of the fiber, as well as overcoming the additional problems described above and known with prior (smaller diameter air void) photonic crystal fiber designs.

Summary of the Invention

In accordance with the teachings of the present invention, a fiber optic waveguide is disclosed. The fiber optic waveguide includes a core region, and a cladding region surrounding the core region. The cladding region includes an inner cladding region and an outer cladding region. The inner cladding region includes a lattice of larger diameter columns. The diameter of the columns may approach the pitch or spacing between the lattice of columns. The core region functions as a defect in the lattice of larger diameter columns for guiding light along the fiber optic waveguide. The core region may be formed from a high index material and the inner cladding region may be formed from a material having a refractive index lower than the refractive index of the core region. The outer cladding region is formed from a material having a refractive index equal to or lower than the refractive index of the inner cladding region.

As part of the present invention, the structure of the photonic crystal fiber has been modified to include larger diameter columns in order to improve the bend loss performance characteristics of the fiber. The result is a photonic crystal fiber with extremely high resistance to bend loss. The fiber core can be made larger or smaller for creating a multimode fiber or a single mode fiber, each having the improved bend performance characteristics.

It is to be understood that both the foregoing general description and the following detailed description are merely exemplary of the invention, and are intended to provide an

overview or framework for understanding the nature and character of the invention as it is claimed. The accompanying drawings are included to provide a further understanding of the invention, and are incorporated in and constitute a part of this specification. The drawings illustrate various features and embodiments of the invention, and together with the description serve to explain the principles and operation of the invention.

Brief Description of the Drawings

The various advantages of the present invention will become apparent to one skilled in the art by reading the following specification and appended claims, and by referencing the following drawings in which:

Figure 1 is a perspective view of an exemplary two-dimensional photonic crystal structure;

Figure 2 is a cross-sectional view of a prior art photonic crystal fiber having smaller diameter columns which produces undesirable bend loss characteristics;

Figure 3 is a graph showing the bend loss characteristics of the photonic crystal fiber of Figure 2 as a result of the smaller diameter columns;

Figure 4 is a cross-sectional view of a photonic crystal fiber having larger diameter air columns in accordance with a preferred embodiment of the present invention;

Figure 5 is a cross-sectional view of a photonic crystal fiber having larger diameter all-glass columns in accordance with an alternate preferred embodiment of the present invention;

Figure 6 is a cross-sectional view of a photonic crystal fiber having larger diameter air or glass columns and a larger diameter (multimode) core region in accordance with an alternate preferred embodiment of the present invention; and

Figure 7 is a graph showing the experimental results (pin array results) of the photonic crystal fiber of Figure 4.

Detailed Description of the Preferred Embodiments

Reference will now be made in detail to the present preferred embodiments of the invention, examples of which are illustrated in the accompanying drawings. Wherever possible, the same reference numerals will be used throughout the drawings to refer to the same or like parts.

Referring now to Figure 4, a cross-sectional view of photonic crystal fiber (PCF)

30 is shown in accordance with a preferred embodiment of the present invention. PCF 30 includes a low index inner cladding region 32 formed around a high index fiber core region 34. The inner cladding region 32 comprises a periodic lattice of large diameter columns 36. As part of PCF 30, the large diameter columns 36 are formed from air which produce air void columns 36. The preferred pitch spacing Λ (lambda) of the large diameter columns 36 is approximately $\Lambda = 4.4$ microns. However, variation of the pitch spacing is within the scope of the present invention. The structure of the inner cladding region 32 shown in Figure 4 can generally be defined by the relationship $d/\Lambda = 0.8$. Accordingly, the diameter (d) of columns 36 with respect to the pitch (Λ) is over three times larger than the diameter of air voids 20 of PCF 16 (Figure 2).

The diameter (d) of the columns 36, whether air or solid glass, can also take on a range of values. Optical fibers have been manufactured with columns having a lower diameter to pitch ratio defined by $d/\Lambda = 0.4$. Experimental results show that such a fiber maintains excellent bend loss characteristics, and is endlessly single mode. A diameter to pitch ratio of $0.2 <= d/\Lambda < 0.45$ produces a photonic crystal fiber which is endlessly single mode and has improved bend loss characteristics over PCF 16 of Figure 2. Experimental data also shows that a photonic crystal fiber having larger diameter columns 36 can be manufactured to have a larger diameter to pitch ratio as high as $d/\Lambda = 0.9$. Experimental results show that such a fiber maintains excellent bend loss characteristics, but functions as a multimode fiber. Accordingly, the preferred range for the diameter to pitch ratio for the larger diameter air columns is $0.3 <= d/\Lambda <= 0.9$. The resulting photonic crystal fibers maintain excellent bend loss characteristics, and can be either single mode or multimode fibers depending upon the ratio.

A particular feature of PCF 30 is that the core region 34 does not include a large diameter air column 36. As a result, the core region 34 functions as a defect in the lattice structure for guiding light through the waveguide. The fiber core region 34 is preferably formed from silica, which has an index (n) of about $n = 1.45$. However, the core region 34 may also be formed from doped silica for altering the index characteristics. An outer cladding region 38, preferably formed from doped silica and having an index which is at least higher than the refractive index of the inner cladding region 32, surrounds the inner cladding region 32. While not specifically shown, an absorptive polymer coating is

typically applied to the outer surface of the outer cladding region 38 and optical fiber 30.

With reference to Figure 5, a cross-sectional view of photonic crystal fiber (PCF) 40 is shown in accordance with an alternate preferred embodiment of the present invention. PCF 40 includes a low index inner cladding region 42 formed around a high index fiber core region 44. The inner cladding region 42 comprises a periodic lattice of large diameter columns 46. As part of PCF 40, the large diameter columns 46 are formed from solid glass. The preferred pitch spacing Λ (lambda) of the large diameter columns 46 is approximately $\Lambda = 4.4$ microns. However, the pitch (Λ) can be chosen within the range of 1 micron $<= \Lambda <=$ 20 microns with a preferred range of 2 microns $<= \Lambda <=$ 10 microns. The structure of the inner cladding region 42 is generally defined by the relationship $d/\Lambda = 0.8$. Thus, the diameter (d) of the glass columns 46 with respect to the pitch (Λ) is over three times larger than the diameter of air voids 20 of PCF 16 (Figure 2). Experimental results show that a diameter to pitch ratio defined by $d/\Lambda = 0.6$ for the glass columns 46 produces a photonic crystal fiber which is single mode for wavelengths in the range of 500 nanometers to 2 micrometers.

A particular feature of PCF 40 is that the core region 44 does not include a large diameter column 46. As a result, the core region 44 functions as a defect in the lattice structure for guiding light through the waveguide. The fiber core region 44 is preferably formed from silica, which has an index (n) of about $n = 1.45$. However, the core region 44 may also be formed from doped silica for altering the index characteristics. An outer cladding region 48, preferably formed from doped silica and having an index which is at least higher than the refractive index of the inner cladding region 42, surrounds the inner cladding region 42. While not specifically shown, an absorptive polymer coating is typically applied to the outer surface of the outer cladding region 48 and optical fiber 40.

Turning now to Figure 6, a cross-sectional view of photonic crystal fiber (PCF) 50 is shown in accordance with an alternate preferred embodiment of the present invention. PCF 50 includes a low index inner cladding region 52 formed around a high index fiber core region 54. The inner cladding region 52 comprises a periodic lattice of large diameter columns 56. As part of PCF 50, the large diameter columns 56 may be formed from either air voids or solid glass. The preferred pitch spacing Λ (lambda) of the large diameter columns 56 is approximately $\Lambda = 4.4$ microns. The structure of the inner cladding region

52 is generally defined by the relationship $d/\Lambda = 0.8$. Thus, the diameter (d) of columns 56 with respect to the pitch (Λ) is over three times larger than the diameter of air voids 20 of PCF 16 (Figure 2).

A particular feature of PCF 50 is that the core region 54 does not include a large diameter column 56, and the six inner most columns 56 have been eliminated thereby producing a larger diameter core region 54. As a result, the core region 54 functions as a defect in the lattice structure for guiding light through the waveguide. The core region 54 also produces a multimode optical waveguide because of its larger diameter. The fiber core region 54 is preferably formed from silica, which has an index (n) of about n = 1.45. However, the core region 54 may also be formed from doped silica for altering the index characteristics. An outer cladding region 58, preferably formed from doped silica and having an index which is at least higher than the refractive index of the inner cladding region 52, surrounds the inner cladding region 52. While not specifically shown, an absorptive polymer coating is typically applied to the outer surface of the outer cladding region 58 and optical fiber 50.

Figure 7 is a graph showing the pin array results of the PCF 30 of Figure 4. The pin array is a standardized device used for assessing the bend performance of an optical fiber. As shown in Figure 7, for all wavelengths, the pin array loss was below 0.04 dB. The loss at 1550 nm was measured at 0.014 dB, and at many wavelengths the measurable loss is below the resolution of the measuring device.

The experimental results of Figure 7 show that PCF 30 having a diameter to pitch ratio of about $d/\Lambda = 0.8$ is attractive for multimode applications. Measurement shows that PCF 30 has a numerical aperture (NA) of about 0.4. PCF 30 was also found to have a limited number of modes (modeled to have 6 non-degenerate modes), and far fewer modes than Ge-doped multimode fibers.

The foregoing discussion discloses and describes exemplary embodiments of the present invention. One skilled in the art will readily recognize from such discussion, and from the accompanying drawings and claims, that various changes, modifications and variations can be made therein without departing from the spirit and scope of the invention as defined in the following claims.

What is claimed is:

1. A fiber optic waveguide comprising:

a core region;

a cladding region surrounding the core region, the cladding region including an inner cladding region and an outer cladding region, the inner cladding region having a lattice of large diameter columns;

the lattice of large diameter columns having a diameter (d) to pitch (Λ) ratio defined by the relationship d/Λ greater than or equal to 0.3.

2. The waveguide of Claim 1 wherein the core region functions as a defect in the lattice of large diameter columns for guiding light within the fiber optic waveguide.

3. The waveguide of Claim 1 wherein the lattice of large diameter columns are formed from columns of air.

4. The waveguide of Claim 1 wherein the lattice of large diameter columns are formed from columns of solid material.

5. The waveguide of Claim 4 wherein the columns of solid material are glass.

6. The waveguide of Claim 4 wherein the columns of solid material are low index glass.

7. The waveguide of Claim 1 wherein the core region is approximately the same diameter as one of the columns forming the inner cladding region for producing single mode characteristics in the waveguide.

8. The waveguide of Claim 1 wherein the core region is substantially larger than one of the columns forming the inner cladding region for producing multimode characteristics in the waveguide.

9. The waveguide of Claim 1 wherein the diameter to pitch ratio is about $d/\Lambda = 0.45$.

10. A fiber optic waveguide comprising:

a core region;

a cladding region surrounding the core region, the cladding region including an inner cladding region and an outer cladding region, the inner cladding region having a lattice of large diameter columns;

the lattice of large diameter columns having a diameter (d) to pitch (Λ) ratio defined by the relationship $0.3 <= d/\Lambda <= 0.9$.

11. The waveguide of Claim 10 wherein the lattice of large diameter columns are formed from columns of air.

12. The waveguide of Claim 10 wherein the lattice of large diameter columns are formed from columns of low index glass.

13. The waveguide of Claim 10 wherein the core region is approximately the same diameter as one of the columns forming the inner cladding region for producing single mode characteristics in the waveguide.

14. The waveguide of Claim 10 wherein the core region is substantially larger than one of the columns forming the inner cladding region for producing multimode characteristics in the waveguide.

15. The waveguide of Claim 10 wherein the diameter to pitch ratio is about $d/\Lambda = 0.8$.

16. A fiber optic waveguide comprising:

a high index core region;

a low index cladding region surrounding the core region, the cladding region including an inner cladding region and an outer cladding region, the inner cladding region having a lattice of large diameter columns;

the lattice of large diameter columns having a diameter (d) to pitch (Λ) ratio defined by the relationship $d/\Lambda = 0.8$, wherein the core region is approximately the same diameter as one of the columns forming the inner cladding region for

producing single mode characteristics in the waveguide.

17. The waveguide of Claim 16 wherein the lattice of large diameter columns are formed from columns of air.

18. The waveguide of Claim 16 wherein the lattice of large diameter columns are formed from columns of low-index glass.

FIG.1
PRIOR ART

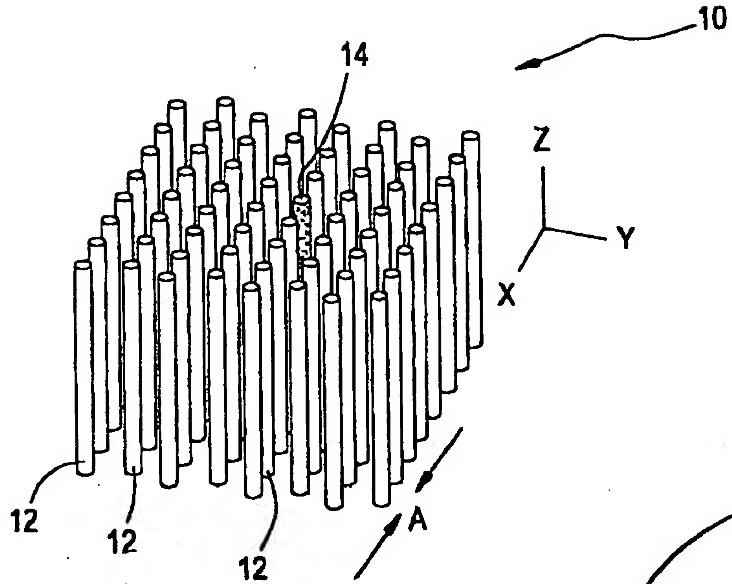


FIG.2
PRIOR ART

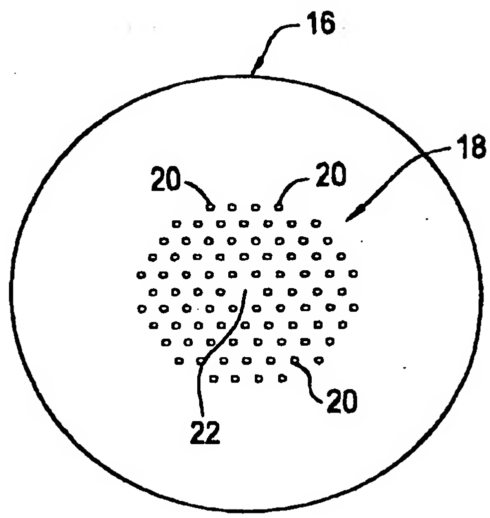


FIG.3

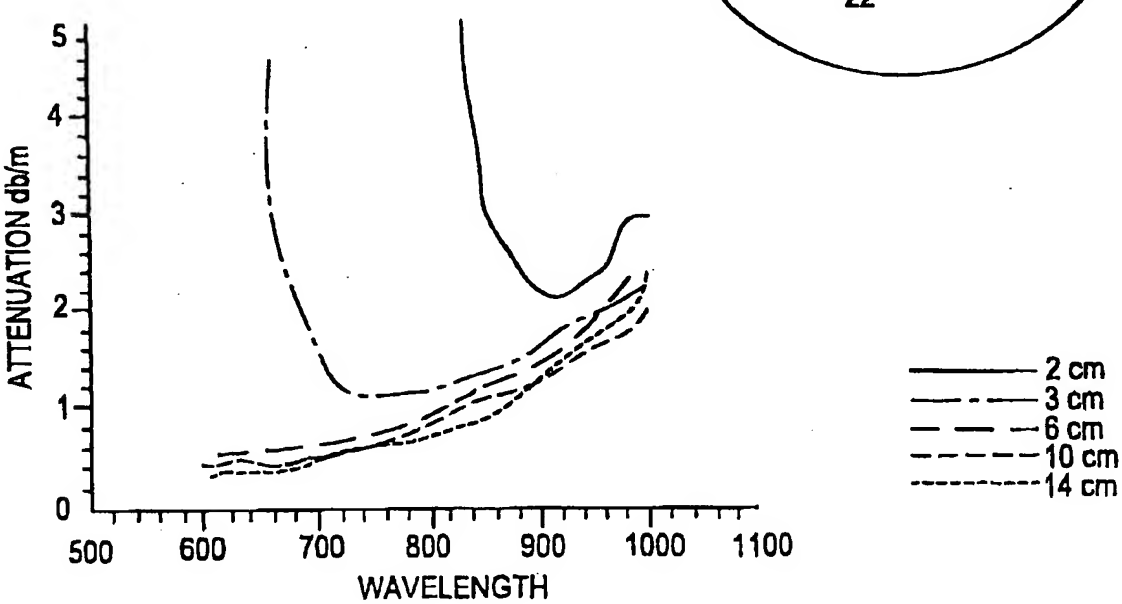


FIG. 4

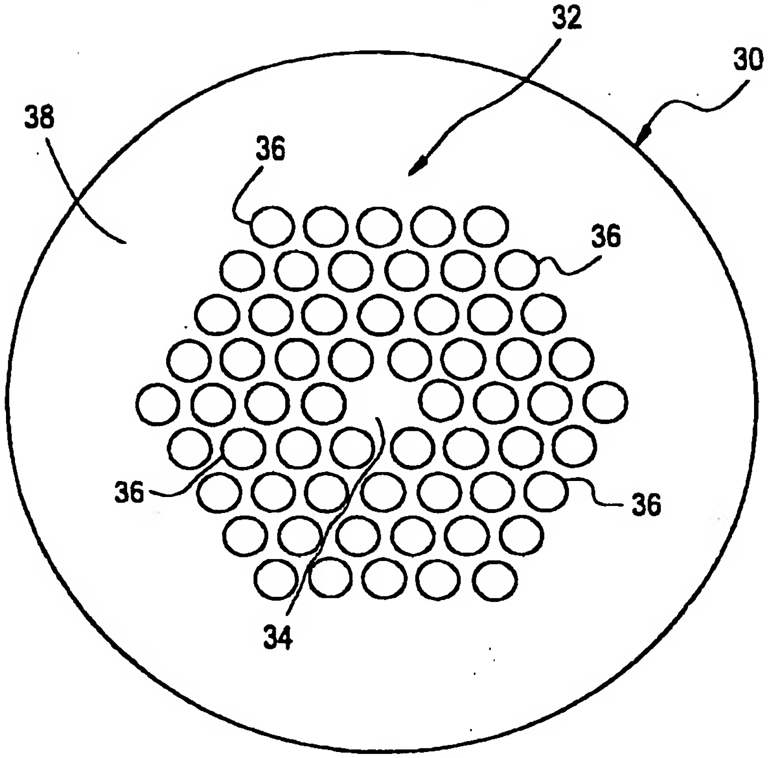


FIG. 5

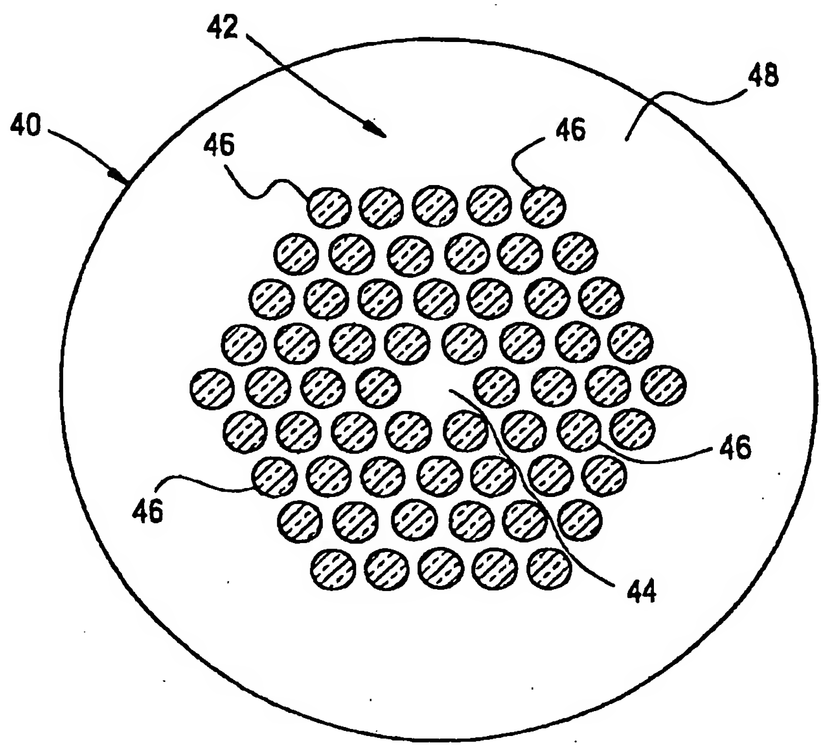
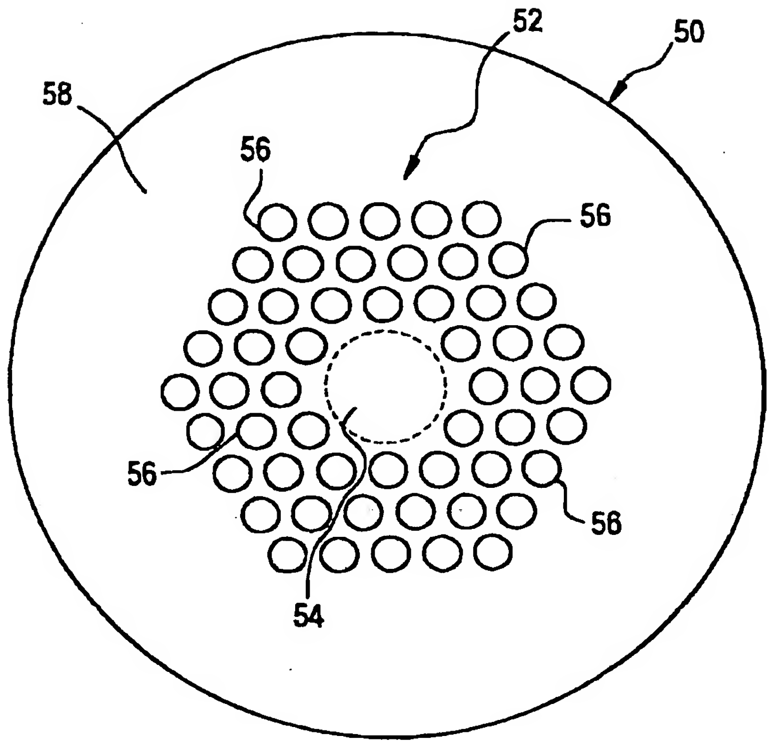


FIG. 6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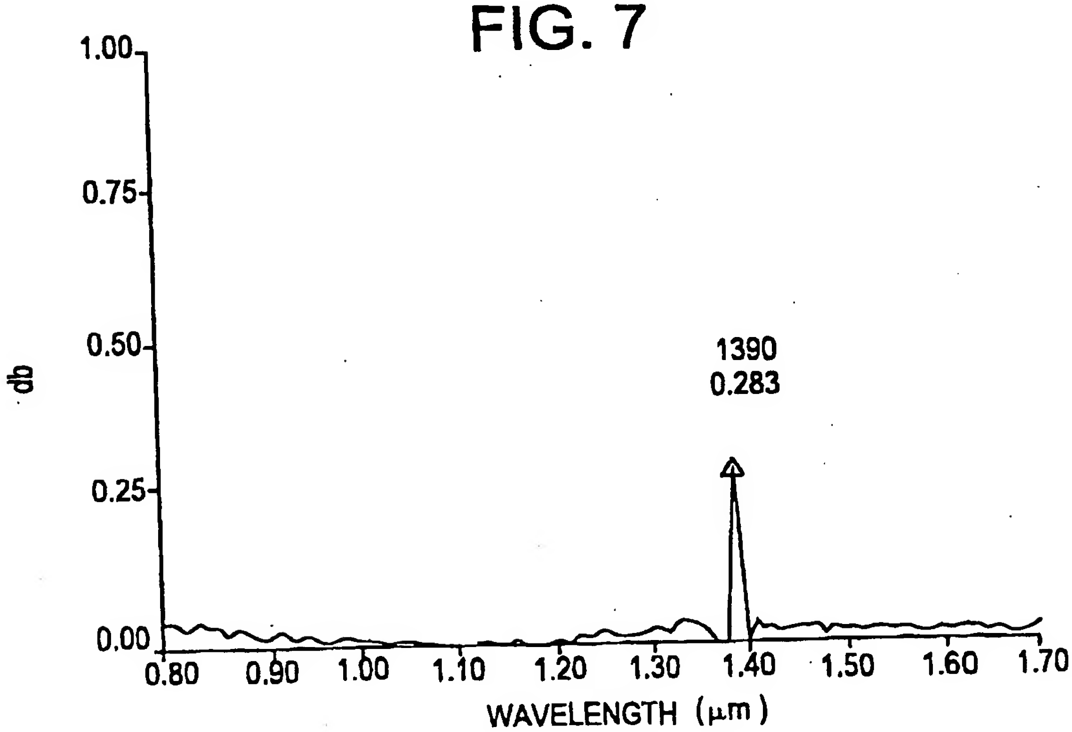
56
54

FIG. 7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